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## Search for a new resonance decaying to a $W$ or $Z$ boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$ final states with the ATLAS Detector

The ATLAS Collaboration

### Abstract

A search for a new resonance decaying to a  $W$  or  $Z$  boson and a Higgs boson in the  $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$  final states is performed using  $20.3 \text{ fb}^{-1}$  of  $pp$  collision data recorded at  $\sqrt{s} = 8 \text{ TeV}$  with the ATLAS detector at the Large Hadron Collider. The search is conducted by examining the  $WH/ZH$  invariant mass distribution for a localized excess. No significant deviation from the Standard Model background prediction is observed. The results are interpreted in terms of constraints on the Minimal Walking Technicolor model and on a simplified approach based on a phenomenological Lagrangian of Heavy Vector Triplets.

# 1 Introduction

Although the Higgs boson discovery by the ATLAS [1] and CMS [2] collaborations imposes strong constraints on theories beyond the Standard Model (SM), the extreme fine tuning in quantum corrections required to have a light fundamental Higgs boson [3, 4] suggests that the SM may be incomplete, and not valid beyond a scale of a few TeV. Various dynamical electroweak symmetry breaking scenarios which attempt to solve this naturalness problem, such as Minimal Walking Technicolor [5, 6, 7, 8], Little Higgs [9], or composite Higgs models [10, 11], predict the existence of new resonances decaying to a vector boson plus a Higgs boson.

Using the full dataset collected by the ATLAS detector at 8 TeV centre-of-mass energy at the Large Hadron Collider, a search is performed for a heavy resonance decaying to  $VH$ , where  $V$  is a  $W$  or  $Z$  boson and  $H$  is the SM Higgs boson. This analysis looks for the leptonic decay of the  $W$  or  $Z$  boson and the Higgs decay into a  $b$ -quark pair. Therefore the selected final states are: zero charged leptons targeting  $Z(\rightarrow \nu\nu)b\bar{b}$  decays, one charged lepton  $W(\rightarrow \ell\nu)b\bar{b}$ , and two oppositely charged leptons  $Z(\rightarrow \ell\ell)b\bar{b}$  where  $\ell = e, \mu$ . The search is performed by examining the distribution of the reconstructed  $VH$  mass ( $m_{VH}$ ) for a localized excess. The signal strength and the background normalization are determined from a likelihood fit to the data distribution in the three channels studied.

As a benchmark, the Minimal Walking Technicolor model (MWT) is used, a model with strongly coupled dynamics. This model predicts two triplets of resonances,  $R_1^{\pm,0}$  and  $R_2^{\pm,0}$ , one of which is a vector and the other an axial-vector, that couple to vector bosons with strength  $\tilde{g}$  and to fermions with  $g/\tilde{g}$ , where  $g$  is the weak SU(2) coupling constant. The bare axial-vector mass  $m_A$  determines the masses of  $R_1$  and  $R_2$ , with the lower mass resonance  $R_1$  having a mass close to  $m_A$ . Recent lattice simulations in this model [12, 13, 14] predict masses close to 2 TeV. The decay channels  $R_{1,2}^{\pm} \rightarrow WH$  and  $R_{1,2}^0 \rightarrow ZH$ , lead to  $Wb\bar{b}$  and  $Zb\bar{b}$  final states.

A simplified approach based on a phenomenological Lagrangian [15] that incorporates Heavy Vector Triplets (HVT), which allows the interpretation of the results in a model-independent way, is also used. Here, the new heavy vector bosons,  $V'^{\pm,0}$ , couple to the Higgs and SM gauge bosons via a combination of parameters  $g_V c_H$  and to the fermions via the combination  $(g^2/g_V) c_F$ . The parameter  $g_V$  represents the strength of the new vector boson interaction, while  $c_H$  and  $c_F$ , which represent the couplings to the Higgs and the fermions respectively, are expected to be of order unity in most models. Two benchmark models [15] are used here. In the first model, referred to as *model A*, the branching fractions to fermions and gauge bosons are comparable, as in some extensions of the SM gauge group [16]. For *model B*, fermionic couplings are suppressed, as for example in a composite Higgs model [17].

The three final states presented in this Letter have been extensively studied for non-resonant production in ATLAS [18]. Moreover, a search for a pseudoscalar resonance in the  $\ell\ell b\bar{b}$  and  $\nu\nu b\bar{b}$  channels has already been published by ATLAS, setting limits on two-Higgs-doublet models [19]. Other searches for particles occurring in MWT and HVT models have been conducted by the ATLAS [20, 21] and CMS [22] collaborations.

## 2 The ATLAS detector

The ATLAS detector [23] is a general-purpose particle detector used to investigate a broad range of physics processes. It includes inner tracking devices surrounded by a superconducting solenoid, electro-

magnetic and hadronic calorimeters and a muon spectrometer. The inner detector (ID) provides precision tracking of charged particles with pseudorapidity<sup>1</sup>  $|\eta| < 2.5$ . The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . It is composed of sampling calorimeters with either liquid argon (LAr) or scintillator tiles as the active medium. The muon spectrometer consists of three large superconducting toroids and a system of trigger chambers and precision tracking chambers that provide triggering and tracking capabilities in the ranges of  $|\eta| < 2.4$  and  $|\eta| < 2.7$  respectively.

The ATLAS detector has a three-level trigger system to select events for offline analysis.

### 3 Data and Monte Carlo samples

This analysis is based on  $\sqrt{s} = 8$  TeV  $pp$  collision data corresponding to  $20.3 \pm 0.6 \text{ fb}^{-1}$  [24]. The data used in the  $\ell\nu b\bar{b}$  final state were collected using single-electron and single-muon triggers with transverse momentum ( $p_T$ ) thresholds from 24 to 60 GeV. The data used in the  $\ell\ell b\bar{b}$  final state were collected using a combination of single-electron, single-muon, dielectron ( $ee$ ) and dimuon ( $\mu\mu$ ) triggers. The  $p_T$  thresholds for the  $ee$  and  $\mu\mu$  triggers vary from 12 to 13 GeV. The data used in the  $\nu\nu b\bar{b}$  final state were collected using a trigger that requires a missing transverse momentum ( $E_T^{\text{miss}}$ ) with magnitude  $E_T^{\text{miss}}$  greater than 80 GeV.

Simulated Monte Carlo (MC) samples for the MWT benchmark model use the implementation [25] in MADGRAPH5 [26], with the Higgs boson mass set to 126 GeV. The parameter  $\tilde{g}$  is set to 2 for signal generation. Constraints on other values of this parameter can be set using the same samples since the kinematic distributions do not depend on  $\tilde{g}$ . The parameter  $S$ , which is an approximate value [27] of the Peskin–Takeuchi  $S$  parameter [28] which measures potential new contributions to electroweak radiative corrections, is set to 0.3, in accordance with the recommendations in Ref. [29].

Signal samples for the HVT model are also generated with MADGRAPH5. The parameter  $c_F$  is assumed to be the same for quarks and leptons including third-generation fermions. Other parameters involving more than one heavy vector boson,  $g_V c_{VVV}$ ,  $g_V^2 c_{VVHH}$  and  $c_{VWW}$ , have negligible effect on the overall cross sections for the processes of interest here. For all signal events, parton showering and hadronization is performed with PYTHIA8 [30, 31] and the CTEQ6L1 [32] parton distribution functions (PDFs) are used. Benchmark signal samples are generated for a range of resonance masses from 300 to 2000 GeV in steps of 100 GeV.

MC samples are used to model the shape and normalization of most SM background processes, although some are later adjusted using data-based corrections extracted from control samples. The production of  $W$  and  $Z$  bosons in association with jets is simulated with SHERPA 1.4.1 [33] using the CT10 PDFs [34]. Top quark pair production is simulated using POWHEG [35, 36] with the POWHEG-BOX program [37] interfaced to PYTHIA6, using the CTEQ6L1 PDFs. In this analysis, the final normalizations of these dominant backgrounds are constrained by the data, but theoretical cross sections are used to optimize the selection. The cross sections are calculated at NNLO accuracy for  $W/Z$ +jets [38] and at NNLO+NNLL accuracy for  $t\bar{t}$  [39]. Single top quark production is simulated with POWHEG and ACERMC [40] interfaced to PYTHIA6, using the CTEQ6L1 PDFs, and the cross sections are taken from Ref. [41]. Diboson production

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

( $WW, WZ, ZZ$ ) is simulated using POWHEG interfaced to PYTHIA8, using the CT10 PDFs, and the cross sections are obtained at NLO from MCFM [42]. Finally, SM Higgs boson production in association with a  $W/Z$  boson is simulated using PYTHIA8 with the CTEQ6L1 PDFs, and considered as a background in this search. It is scaled to the SM cross section [18].

All MC simulated samples include the effect of multiple  $pp$  interactions in the same and neighbouring bunch crossings (pile-up) by overlaying simulated minimum-bias events on each generated signal or background event. The number of overlaid events is such that the distribution of the number of interactions per  $pp$  bunch crossing in the simulation matches that observed in the data, with on average 21 interactions per bunch crossing. The generated samples are processed through the GEANT4-based ATLAS detector simulation [43, 44] or a fast simulation using a parameterization of the performance of the calorimetry and GEANT4 for the other parts of the detector [45]. Simulated events are reconstructed with the standard ATLAS reconstruction software used for collision data.

## 4 Object reconstruction

The physics objects used in this analysis are electrons, muons, jets and missing transverse momentum.

Electrons are identified for  $|\eta| < 2.47$  and  $p_T > 7$  GeV from energy clusters in the electromagnetic calorimeter that are matched to tracks in the inner detector [46]. Quality requirements based on the calorimeter cluster and track are applied to reduce contamination from jets.

Muons are reconstructed in the muon spectrometer in the range  $|\eta| < 2.7$  and  $p_T > 4$  GeV [47]. For  $|\eta| < 2.5$  the muon spectrometer track must be matched with a track in the inner detector and information from both is used to reconstruct the momentum. Muons considered for this analysis must have  $p_T > 7$  GeV.

Lepton candidates are required to be isolated to reduce the multijet background. The scalar sum of the transverse momenta of tracks with  $p_T > 1$  GeV within a cone of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$  around the lepton track (tracking isolation) is required to be less than 10% of the lepton  $p_T$ .

Jets are reconstructed using the anti- $k_t$  algorithm [48] with radius parameter  $R = 0.4$ . The jet transverse momentum is corrected for energy losses in passive material, for the non-compensating response of the calorimeter, and for any additional energy due to multiple  $pp$  interactions [49]. Jets are required to have  $p_T > 30$  GeV and  $|\eta| < 4.5$ . To reject low- $p_T$  jets from pile-up, for jets with  $p_T < 50$  GeV and  $|\eta| < 2.5$ , the scalar sum of the  $p_T$  of associated tracks, originating from the reconstructed primary vertex, is required to be at least 50% of the scalar sum of the  $p_T$  of all associated tracks. To avoid double-counting of leptons and jets, an overlap removal procedure is applied [18].

In the pseudorapidity range  $|\eta| < 2.5$ , jets originating from  $b$ -quarks are identified using a multi-variate  $b$ -tagging algorithm [50]. This has an efficiency of 70% and a misidentification rate of less than 1% for selecting jets initiated by light quarks or gluons and of about 20% for jets initiated by  $c$ -quarks, as determined from  $t\bar{t}$  MC events.

The missing transverse momentum is calculated as the negative of the vectorial sum of the calorimeter-based transverse momenta of all electrons, jets, and calibrated calorimeter clusters within  $|\eta| < 4.9$  that are not associated with any other objects [51], as well as muon momenta. In addition, a track-based missing transverse momentum ( $\vec{p}_T^{\text{miss}}$ , with magnitude  $p_T^{\text{miss}}$ ) is used, calculated as the negative vectorial sum of the track-based transverse momenta of objects with  $|\eta| < 2.4$  associated with the primary vertex.

## 5 Event selection and reconstruction

Events are categorized into the  $\nu b\bar{b}$ ,  $\ell\nu b\bar{b}$  or  $\ell\ell b\bar{b}$  channels if they have zero, one or two reconstructed charged leptons respectively. All categories require at least two jets in the pseudorapidity range  $|\eta| < 2.5$  (central jets). The channels are further subdivided into categories of events containing one or two  $b$ -tagged jets; events with zero or  $\geq 3$   $b$ -tagged jets are rejected. The Higgs boson candidate (and its mass  $m_{b\bar{b}}$ ) is reconstructed from the two  $b$ -tagged jets or, for 1- $b$ -tag events, the  $b$ -tagged jet and the highest- $p_T$  remaining central jet. In order to suppress  $W/Z$ +jets background, at least one of the jets must have  $p_T > 45$  GeV and the invariant mass of the dijet pair must be in the range  $105 < m_{b\bar{b}} < 145$  GeV, consistent with the Higgs mass. In order to reduce the  $t\bar{t}$  background in the  $\nu b\bar{b}$  and  $\ell\nu b\bar{b}$  channels, events are rejected if they contain four or more jets. To improve the resolution of the  $VH$  mass a constraint to the Higgs boson mass is applied by scaling the Higgs boson candidate jet momenta by  $m_H/m_{b\bar{b}}$  ( $m_H = 125$  GeV). Further channel-specific cuts are applied as outlined below.

### 5.1 $\nu b\bar{b}$ channel

Events are selected with  $E_T^{\text{miss}} > 120$  GeV and  $p_T^{\text{miss}} > 30$  GeV. A requirement is made on  $H_T$ , defined as the scalar sum of the  $p_T$  of all jets, in order to keep a high trigger efficiency:  $H_T > 120$  GeV ( $> 150$  GeV) for events with two (three) jets. Selections are also applied on the angle between the jets used for reconstructing the Higgs candidate,  $\Delta R_{b\bar{b}}$ , to suppress the  $W/Z$ +jets background [18]: for  $120 < E_T^{\text{miss}} < 160$  GeV,  $0.7 < \Delta R_{b\bar{b}} < 1.8$ ; for  $160 < E_T^{\text{miss}} < 200$  GeV,  $\Delta R_{b\bar{b}} < 1.8$ ; for  $E_T^{\text{miss}} > 200$  GeV,  $\Delta R_{b\bar{b}} < 1.4$ . Events containing an electron or muon passing the selection cuts described in Sec. 4 are removed.

In events with real  $E_T^{\text{miss}}$  the directions of  $E_T^{\text{miss}}$  and  $p_T^{\text{miss}}$  are expected to be similar. In events with fake  $E_T^{\text{miss}}$  arising from a jet energy fluctuation, the direction of  $E_T^{\text{miss}}$  should be close to the direction of the poorly measured jet. Therefore additional criteria are imposed on angular quantities in order to suppress the multijet background: the azimuthal angle between  $E_T^{\text{miss}}$  and  $p_T^{\text{miss}}$ ,  $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < \pi/2$ ; the minimum azimuthal angle between  $E_T^{\text{miss}}$  and any jet,  $\min[\Delta\phi(E_T^{\text{miss}}, \text{jet})] > 1.5$ ; and the azimuthal angle between  $E_T^{\text{miss}}$  and the jet pair combination used to reconstruct the Higgs candidate,  $\Delta\phi(E_T^{\text{miss}}, b\bar{b}) > 2.8$ .

It is not possible to accurately reconstruct the invariant mass of the  $ZH$  system due to the missing neutrinos, so the transverse mass is used as the final discriminant:  $m_{VH}^T = \sqrt{(E_T^{b\bar{b}} + E_T^{\text{miss}})^2 - (p_T^{b\bar{b}} + p_T^{\text{miss}})^2}$ , where  $p_T^{b\bar{b}}$  is the transverse momentum of the Higgs candidate. The total acceptance times selection efficiency varies from 15% for  $m_{R_1} = 400$  GeV, to 30% for  $m_{R_1} = 1000$  GeV and down to 2% for  $m_{R_1} = 2000$  GeV. The drop at very high masses is due to the merging of the jets.

### 5.2 $\ell\nu b\bar{b}$ channel

In order to suppress the multijet background and ensure the single-lepton triggers are fully efficient, tighter identification criteria are placed on the lepton in this channel. The lepton  $p_T$  requirement is raised to  $p_T > 25$  GeV and, for the muon channel, the pseudorapidity is restricted to  $|\eta| < 2.5$ . Moreover, the tracking isolation is tightened and required to be less than 4% of the lepton  $p_T$ . Similarly, the sum of transverse energy deposits in the calorimeter within a cone of  $\Delta R = 0.3$  around the lepton, excluding the

transverse energy due to the lepton and the correction for the expected pile-up contribution, is required to be less than 4% of the lepton  $p_T$ .

The multijet background is further reduced by requiring  $\Delta\phi(E_T^{\text{miss}}, \text{jet}) > 1.0$ .  $W$  boson candidates are selected by requiring  $E_T^{\text{miss}} > 30$  GeV and the transverse mass reconstructed from the lepton and  $E_T^{\text{miss}}$ ,  $m_W^T = \sqrt{2 \times E_T^\ell \times E_T^{\text{miss}} \times (1 - \cos\Delta\phi(\ell, E_T^{\text{miss}}))} > 20$  GeV.

The  $WH$  system mass,  $m_{VH}$ , is reconstructed from the lepton, the  $E_T^{\text{miss}}$  and the two jets. The momentum of the neutrino in the  $z$ -direction,  $p_z$ , is obtained by imposing the  $W$  boson mass constraint on the lepton and neutrino system, which leads to a quadratic equation. Here  $p_z$  is taken as either the real component of the complex solutions or the smaller of the two real solutions.

In order to reduce the  $W$ +jets background, a requirement is imposed on the transverse momentum of the  $W$  boson,  $p_T^W > 0.4 \times m_{VH}$ . The cut depends on  $m_{VH}$  since the background is generally produced at low  $p_T^W$ , whereas for signal the mean  $p_T^W$  increases with  $m_{VH}$ . The total acceptance times selection efficiency varies from 8% for  $m_{R_1} = 400$  GeV, to 20% for  $m_{R_1} = 1000$  GeV and down to 2% for  $m_{R_1} = 2000$  GeV.

### 5.3 $\ell\ell b\bar{b}$ channel

Events in this channel are selected by requiring two reconstructed leptons of the same flavour with opposite charge. In order to reduce the multijet background while keeping a high signal acceptance, tighter requirements are placed on one of the leptons. These tighter electrons or muons must have  $p_T > 25$  GeV and, in addition, muons are restricted to  $|\eta| < 2.5$ . A cut on the two-lepton invariant mass of  $83 \text{ GeV} < m_{\ell\ell} < 99 \text{ GeV}$  is imposed to reduce  $t\bar{t}$  and multijet backgrounds. The  $t\bar{t}$  background is further reduced by requiring  $E_T^{\text{miss}} < 60$  GeV.

The invariant mass of the two leptons and two jets is used to reconstruct  $m_{VH}$ .

In order to reduce the dominant  $Z$ +jets background, a selection, optimized for this channel, is imposed on the transverse momentum of the  $Z$  boson:  $p_T^Z > 0.4 \times m_{VH} - 100$  GeV. The total acceptance times selection efficiency varies from 18% for  $m_{R_1} = 400$  GeV, to 30% for  $m_{R_1} = 1000$  GeV and down to 1% for  $m_{R_1} = 2000$  GeV.

## 6 Background estimation

All backgrounds except the multijet background are estimated from simulation, with data-based corrections for the dominant  $W/Z$ +jets background as described in the following. The rate and shape of the multijet (MJ) background are estimated with data-driven methods.

The MJ background is estimated in the 0-lepton channel using an ‘‘ABCD method’’ based on two uncorrelated variables:  $\min[\Delta\phi(E_T^{\text{miss}}, \text{jet})]$  and  $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$ . The data are divided into four regions such that three of the regions are dominated by background. The signal region (A) is defined as explained in Sect. 5. The MJ-dominated region C is obtained by reversing the  $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$  requirement. An MJ template in region A is obtained using events in region C after subtracting the contribution of other backgrounds, taken from simulation. The template is then normalized by a fit to the regions with  $\min[\Delta\phi(E_T^{\text{miss}}, \text{jet})] < 0.4$  [18] (regions B and D with orthogonal  $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}})$  requirements).



In the 1-lepton channel, the MJ background is determined separately for the electron and muon sub-channels. An MJ-background template is obtained from an MJ-dominated region after subtracting the small contribution from the other backgrounds. An MJ-dominated region is obtained by loosening the lepton identification requirements and reversing the isolation criteria. A binned fit of the full  $E_T^{\text{miss}}$  spectrum of the data to the sum of the MJ contribution,  $W/Z$ +jets and other MC contributions is then used to extract the MJ normalization. The templates are validated in a control region enriched in MJ events, selected by reversing the  $E_T^{\text{miss}}$  requirement.

For the 2-lepton channel in the  $ee b\bar{b}$  final state, the MJ background shape is determined by selecting events with reversed electron isolation criteria and its normalization is extracted by fitting the full data  $m_{ee}$  distribution including  $Z$  sidebands. The MJ background in the  $\mu\mu b\bar{b}$  final state is found to be negligible.

The  $W/Z$ +jets simulated samples are split into different components according to the true flavour of the jets, i.e.  $W/Z+qq$ ,  $W/Z+cq$ , where  $q$  denotes a light quark ( $u, d, s$ ) or a gluon, and  $W/Z$  plus heavy flavour (hf). The latter includes:  $W/Z+b\bar{b}$ ,  $W/Z+bq, W/Z+bc, W/Z+cc$ . The normalizations of  $W+cq$ ,  $Z+cq$  and  $W+hf$ ,  $Z+hf$  are free parameters of the global likelihood fit. The scale factors after the fit are all consistent with 1, except for the  $Z+hf$  normalization that is 15% higher as seen in previous measurements [18]. The  $W/Z$ +jets modelling is checked in control regions selected by requiring events with no  $b$ -tagged jets or in the  $m_{b\bar{b}}$  sideband region in the 1-tag and 2-tag channels. A difference between data and simulation is observed in the 0-tag control region and a correction is extracted as a function of the azimuthal angle difference between the two leading- $p_T$  jets,  $\Delta\phi(\text{jet}_1, \text{jet}_2)$ . This is used to reweight the  $Z+qq$  and  $W+qq$  components. After this correction is applied a discrepancy is observed in the  $p_T^{\ell\ell}$  distribution in the 2-lepton channel after the requirement of at least one  $b$ -tagged jet. A correction is extracted and used to reweight the  $Z+cq$  and  $Z+hf$  components. The full procedure is described in detail in Ref. [18].

The background contributions from single top quark and diboson production are normalized to the number of background events predicted by simulation while the  $t\bar{t}$  normalization is a free parameter in the likelihood fit. The description of the shape of the  $t\bar{t}$  background from MC simulation has been validated in samples dominated by top pair events. Good agreement within uncertainties is observed between data and expectation in these validation regions.

The  $t\bar{t}$  control region is defined by requiring exactly one electron and one muon, one of which has  $p_T > 25$  GeV, and two  $b$ -tagged jets. It is included in the likelihood fit to constrain the  $t\bar{t}$  normalization. The scale factor for the  $t\bar{t}$  normalization is found to be  $1.03 \pm 0.04$  after the likelihood fit to the 0- and 2-lepton channel plus the  $t\bar{t}$  control region, and  $0.99 \pm 0.09$  from the fit to the 1-lepton channel. The fit procedure is described in more detail in Sect. 8.

## 7 Systematic uncertainties

The most important experimental systematic uncertainties come from the jet energy scale (JES) and  $b$ -tagging efficiency.

The JES systematic uncertainty arises from several sources including uncertainties from the in-situ calibration, the corrections dependent on pile-up and the jet flavour composition [52]. The fractional systematic uncertainty on the JES ranges from 3% for a 20 GeV jet to 1% for a 1 TeV jet.

The uncertainty due to the jet energy resolution is also considered. It varies from 20% for a jet with  $p_T > 20$  GeV to 5% for a jet with  $p_T > 1$  TeV. The jet energy scale and resolution uncertainties are propagated

to the reconstructed  $E_T^{\text{miss}}$ . The uncertainty on  $E_T^{\text{miss}}$  also has a contribution from hadronic energy that is not included in jets [53].

The  $b$ -tagging efficiency uncertainty depends on jet  $p_T$  and comes mainly from the uncertainty on the measurement of the efficiency in  $t\bar{t}$  events [50]. Uncertainties are also derived for  $c$ - and light-flavour jet tagging [54].

Other experimental systematic uncertainties that have a smaller impact are those on the lepton energy scale and identification efficiency and the efficiency of the triggers.

In addition to the experimental systematic uncertainties, uncertainties are taken into account for possible differences between data and the simulation model that is used for each process. For the background modelling uncertainties the procedure described in Ref. [18] is followed. The  $Z$ +jets and  $W$ +jets backgrounds include uncertainties on the relative fraction of the different flavour components, and shape uncertainties on the modelling of  $m_{b\bar{b}}$ ,  $\Delta\phi(\text{jet}_1, \text{jet}_2)$  and  $p_T^Z$  distributions. For  $t\bar{t}$  production, shape uncertainties are included for the modelling of top quark transverse momentum,  $m_{b\bar{b}}$  and  $m_{VH}$  distributions. The uncertainty on the MJ background shape in the 1-lepton channel is evaluated by using alternative templates obtained by changing the definition of the data sidebands. The uncertainty on the MJ background normalization is taken to be 100%, 30% and 50% for the 0-, 1- and 2-lepton channels, respectively. These are extracted from fits using alternative templates.

The dominant uncertainties on the signal acceptance arise from the choice of PDFs (2–5%) estimated by comparing the default PDFs to other sets, and from the factorization and renormalization scales (5–10%) obtained by varying these up and down by a factor of two.

## 8 Results and limit extraction

The reconstructed mass distributions for events passing the selection are shown in Fig. 1. The background expectation is shown after the profile likelihood fit to the data. Table 1 shows the number of events expected and observed in each final state.

No significant excess of events is observed in the data compared to the prediction from SM background sources. Exclusion limits at the 95% confidence level (CL) are set on the production cross section times the branching fraction for MWT and HVT models. The limits for the charged resonance are obtained by performing the likelihood fit over the  $\ell\nu b\bar{b}$  channel alone, while the  $\ell\ell b\bar{b}$ ,  $\nu\nu b\bar{b}$  channels as well as the  $t\bar{t}$  control region are used for the neutral resonance.

The exclusion limits are calculated with a modified frequentist method [55], also known as  $CL_s$ , and the profile-likelihood test statistic [56], using the binned  $m_{VH}$  mass distributions for  $\ell\nu b\bar{b}$ ,  $\ell\ell b\bar{b}$  and  $\nu\nu b\bar{b}$  final states. Systematic uncertainties and their correlations are taken into account as nuisance parameters. None of the systematic uncertainties considered are significantly constrained or pulled in the likelihood fit. Figure 2 shows 95% CL upper limits on the production cross section multiplied by the branching fraction into  $WH$  and  $ZH$  as a function of the resonance mass separately for the charged  $R_1^\pm$  and for the neutral  $R_1^0$ . The experimental limits are obtained using samples with a single resonance  $R_1$ , where the cross section for  $R_2$  has been set to zero to be less model-dependent. The theoretical predictions for the HVT benchmark *model A* with coupling constant  $g_V = 1$  allow exclusion of  $m_{V^{*0}} < 1360$  GeV ( $m_{V^{*\pm}} < 1470$  GeV). For the MWT model, since there are two resonances of different mass, the results are displayed for the first one,  $R_1^{0,\pm}$ . The excluded regions are  $m_{R_1^0} < 410$  GeV,  $750 < m_{R_1^0} < 1200$  GeV



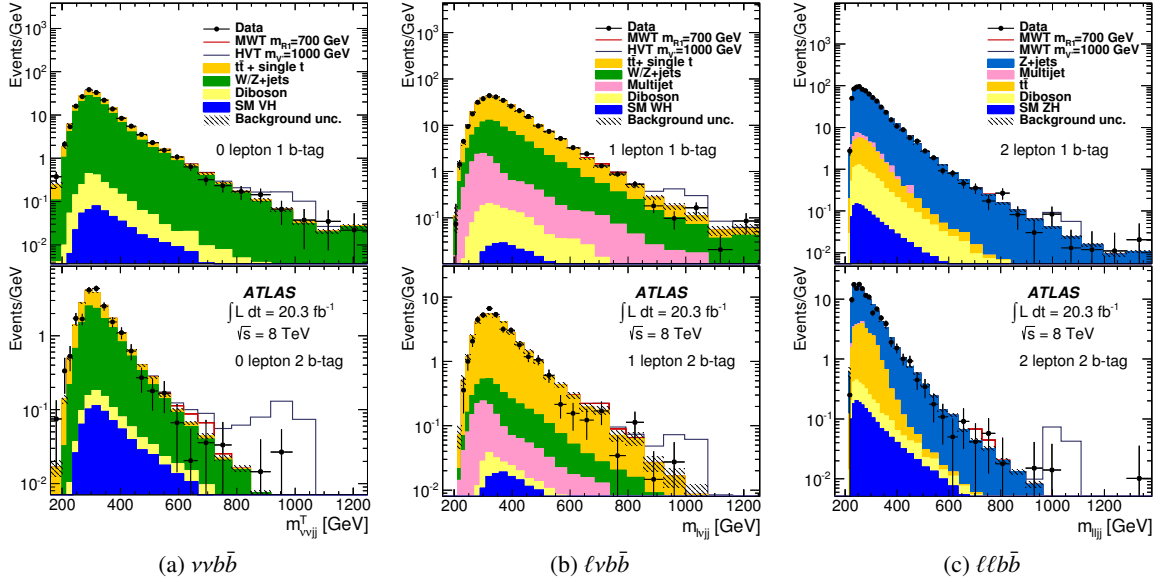


Figure 1: Distributions of the reconstructed (a) transverse mass  $m_{\nu jj}^T$  for the  $\nu\nu b\bar{b}$  final state, (b) invariant mass  $m_{\ell\nu jj}$  for the  $\ell\nu b\bar{b}$  final state and (c) invariant mass  $m_{\ell\ell jj}$  for the  $\ell\ell b\bar{b}$  final state for the 1-b-tag (upper) and 2-b-tag (lower) channels. The background expectation is shown after the profile likelihood fit to the data. Any overflow is included in the last bin. The signals are shown stacked on top of the background and correspond to the benchmark models MWT with  $m_{R1} = 700 \text{ GeV}$  and HVT with  $m_{V'} = 1000 \text{ GeV}$  normalized to the expected cross sections.

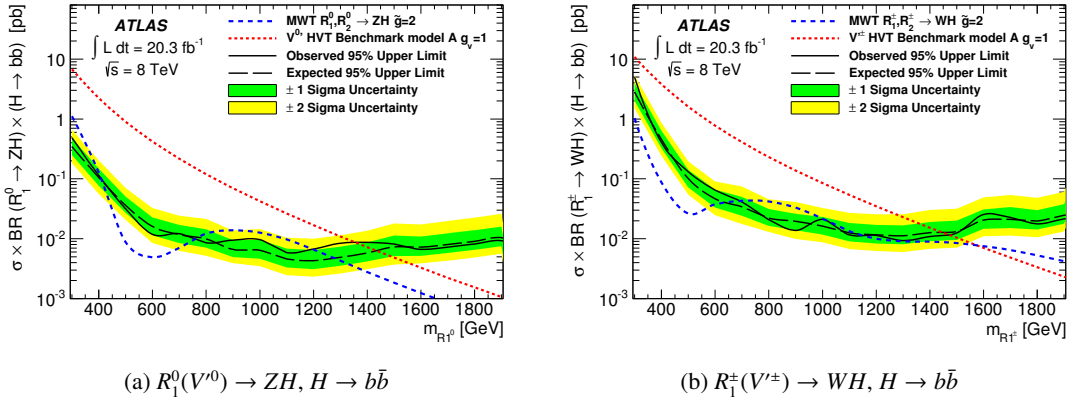


Figure 2: Combined upper limits at the 95% CL for (a) the production cross section of  $R_1^0 (V^0)$  times its branching ratio to  $ZH$  and branching ratio of  $H$  to  $b\bar{b}$  and (b) the production cross section of  $R_1^\pm (V'^\pm)$  times its branching ratio to  $WH$  and branching ratio of  $H$  to  $b\bar{b}$ . The experimental limits are obtained using samples with a single resonance  $R_1$ ; however, the theory curve line for MWT includes both  $R_1$  and  $R_2$ . The dip near 500 GeV in this theory curve is due to the interference between  $R_1$  and  $R_2$  [7].

( $700 < m_{R1^\pm} < 1150 \text{ GeV}$ ). The dip near 500 GeV in this theory curve is due to the interference between  $R_1$  and  $R_2$  [7]. To study the scenario in which the masses of charged and neutral resonances are the same, a combined likelihood fit over all signal regions and the  $t\bar{t}$  control region is also performed. The exclusion contours in the  $\{m_A, \tilde{g}\}$  plane for MWT are presented in Fig. 3. For this result, both resonances predicted by MWT,  $R_1$  and  $R_2$ , are fitted simultaneously and, at each  $\tilde{g}$ , the different branching ratios

Table 1: The number of expected and observed events for the three final states. The expectation is shown after the profile likelihood fit to the data. The quoted uncertainties are the combined systematic and statistical uncertainties. The overall background is more constrained than the individual components, causing the errors of individual components to be anti-correlated.

	Two $b$ -tags		
	$\nu b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\ell b\bar{b}$
Z+jets	$224 \pm 14$	$3.2 \pm 0.2$	$1198 \pm 47$
W+jets	$82 \pm 29$	$61 \pm 21$	–
$t\bar{t}$	$166 \pm 10$	$718 \pm 42$	$321 \pm 14$
Single top	$23.2 \pm 2.6$	$71.3 \pm 8.1$	–
Diboson	$10.1 \pm 1.1$	$2.8 \pm 0.6$	$25.9 \pm 5.8$
SM $VH$	$20.3 \pm 8.1$	$4.6 \pm 1.9$	$24.4 \pm 6.1$
Multijet	$< 3$	$29 \pm 13$	$12.1 \pm 9.1$
Total bkg.	$524 \pm 20$	$889 \pm 28$	$1581 \pm 39$
Data	511	879	1593
	One $b$ -tag		
	$\nu b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\ell b\bar{b}$
Z+jets	$2120 \pm 150$	$53.6 \pm 4.7$	$9120 \pm 550$
W+jets	$1450 \pm 360$	$1892 \pm 590$	–
$t\bar{t}$	$928 \pm 43$	$4650 \pm 370$	$425 \pm 10$
Single top	$221 \pm 25$	$832 \pm 94$	–
Diboson	$48.2 \pm 3.8$	$32.1 \pm 2.5$	$124 \pm 17$
SM $VH$	$13.4 \pm 5.2$	$6.9 \pm 2.7$	$17.6 \pm 7.0$
Multijet	$< 10$	$316 \pm 83$	$139 \pm 70$
Total bkg.	$4761 \pm 69$	$7782 \pm 97$	$9830 \pm 100$
Data	4758	7854	9827

to  $WH$  and  $ZH$  are taken into account. Electroweak precision data, a requirement to remain within the walking technicolor regime and constraints from requiring real-valued physical decay constants exclude a portion of the plane. This analysis is particularly sensitive at high  $\tilde{g}$  values, where the limits exceed those from the dilepton resonance search [21].

The exclusion contours in the HVT parameter space  $\{(g^2/g_V)c_F, g_V c_H\}$  for resonances of mass 1 TeV, 1.5 TeV and 1.8 TeV are shown in Fig. 4 where all three channels are combined, taking into account the branching ratios to  $WH$  and  $ZH$  from the HVT model. These contours are produced by scanning the parameter space, using the HVT tools provided in a web-interface [57, 15].

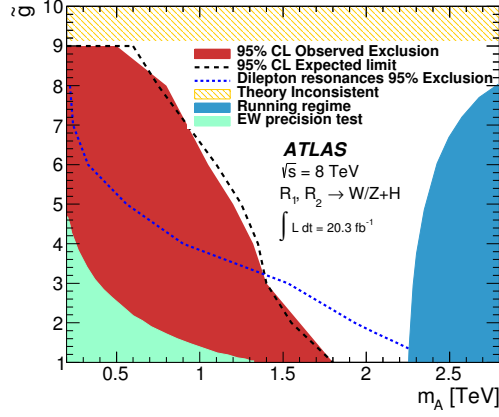


Figure 3: Exclusion contours at 95% CL in the plane of the Minimal Walking Technicolor parameter space defined by the bare axial-vector mass versus the strength of the spin-1 resonance interaction  $\{m_A, \tilde{g}\}$ . Electroweak precision measurements exclude the (green) area in the bottom left corner. The requirement to stay in the walking regime excludes the (blue) area in the right corner. The large (red) area (black dashed line) shows the observed (expected) exclusion. The blue dashed line shows the observed exclusion from the dilepton resonance search [21]. The upper region is excluded due to non-real axial and axial-vector decay constants. Here both resonances predicted by MWT,  $R_1$  and  $R_2$ , are fitted simultaneously.

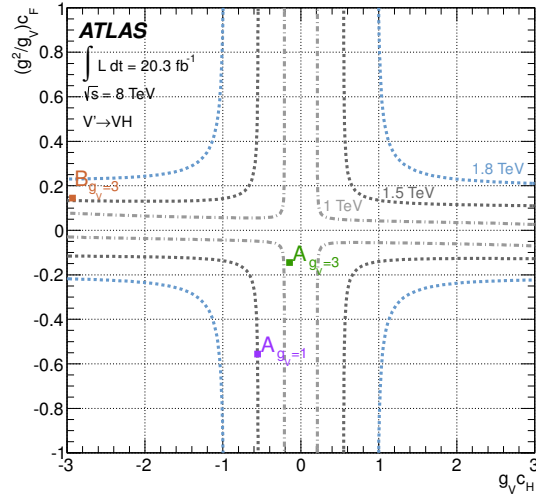


Figure 4: Observed 95% CL exclusion contours in the HVT parameter space  $\{(g^2/g_V)c_F, g_V c_H\}$  for resonances of mass 1 TeV, 1.5 TeV and 1.8 TeV. The areas outside the curves are excluded. Also shown are the benchmark model parameters  $A(g_V=1)$ ,  $A(g_V=3)$  and  $B(g_V=3)$ .

## 9 Summary

A search for a new heavy resonance decaying to  $WH/ZH$  is presented in this Letter. The search is performed using  $20.3 \text{ fb}^{-1}$  of  $pp$  collision data at 8 TeV centre-of-mass energy collected by the ATLAS detector at the Large Hadron Collider. No significant deviations from the SM background predictions are observed in the three final states considered:  $\ell\ell b\bar{b}$ ,  $\ell\nu b\bar{b}$ ,  $\nu\nu b\bar{b}$ . Upper limits are set at the 95% confidence level on the production cross sections of  $R_1$  and  $V'$  for the Minimal Walking Technicolor and Heavy Vector Triplets models respectively. Exclusion contours at 95% CL in the MWT parameter space  $\{m_A, \tilde{g}\}$  and in the HVT parameter space  $\{(g^2/g_V)c_F, g_V c_H\}$  are presented.

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## The ATLAS Collaboration

G. Aad<sup>85</sup>, B. Abbott<sup>113</sup>, J. Abdallah<sup>151</sup>, O. Abdinov<sup>11</sup>, R. Aben<sup>107</sup>, M. Abolins<sup>90</sup>, O.S. AbouZeid<sup>158</sup>, H. Abramowicz<sup>153</sup>, H. Abreu<sup>152</sup>, R. Abreu<sup>30</sup>, Y. Abulaiti<sup>146a,146b</sup>, B.S. Acharya<sup>164a,164b,a</sup>, L. Adamczyk<sup>38a</sup>, D.L. Adams<sup>25</sup>, J. Adelman<sup>108</sup>, S. Adomeit<sup>100</sup>, T. Adye<sup>131</sup>, A.A. Affolder<sup>74</sup>, T. Agatonovic-Jovin<sup>13</sup>, J.A. Aguilar-Saavedra<sup>126a,126f</sup>, S.P. Ahlen<sup>22</sup>, F. Ahmadov<sup>65,b</sup>, G. Aielli<sup>133a,133b</sup>, H. Akerstedt<sup>146a,146b</sup>, T.P.A. Åkesson<sup>81</sup>, G. Akimoto<sup>155</sup>, A.V. Akimov<sup>96</sup>, G.L. Alberghi<sup>20a,20b</sup>, J. Albert<sup>169</sup>, S. Albrand<sup>55</sup>, M.J. Alconada Verzini<sup>71</sup>, M. Aleksa<sup>30</sup>, I.N. Aleksandrov<sup>65</sup>, C. Alexa<sup>26a</sup>, G. Alexander<sup>153</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>113</sup>, G. Alimonti<sup>91a</sup>, L. Alio<sup>85</sup>, J. Alison<sup>31</sup>, S.P. Alkire<sup>35</sup>, B.M.M. Allbrooke<sup>18</sup>, P.P. Allport<sup>74</sup>, A. Aloisio<sup>104a,104b</sup>, A. Alonso<sup>36</sup>, F. Alonso<sup>71</sup>, C. Alpigiani<sup>76</sup>, A. Altheimer<sup>35</sup>, B. Alvarez Gonzalez<sup>90</sup>, D. Álvarez Piqueras<sup>167</sup>, M.G. Alviggi<sup>104a,104b</sup>, B.T. Amadio<sup>15</sup>, K. Amako<sup>66</sup>, Y. Amaral Coutinho<sup>24a</sup>, C. Amelung<sup>23</sup>, D. Amidei<sup>89</sup>, S.P. Amor Dos Santos<sup>126a,126c</sup>, A. Amorim<sup>126a,126b</sup>, S. Amoroso<sup>48</sup>, N. Amram<sup>153</sup>, G. Amundsen<sup>23</sup>, C. Anastopoulos<sup>139</sup>, L.S. Ancu<sup>49</sup>, N. Andari<sup>30</sup>, T. Andeen<sup>35</sup>, C.F. Anders<sup>58b</sup>, G. Anders<sup>30</sup>, J.K. Anders<sup>74</sup>, K.J. Anderson<sup>31</sup>, A. Andreazza<sup>91a,91b</sup>, V. Andrei<sup>58a</sup>, S. Angelidakis<sup>9</sup>, I. Angelozzi<sup>107</sup>, P. Anger<sup>44</sup>, A. Angerami<sup>35</sup>, F. Anghinolfi<sup>30</sup>, A.V. Anisenkov<sup>109,c</sup>, N. Anjos<sup>12</sup>, A. Annovi<sup>124a,124b</sup>, M. Antonelli<sup>47</sup>, A. Antonov<sup>98</sup>, J. Antos<sup>144b</sup>, F. Anulli<sup>132a</sup>, M. Aoki<sup>66</sup>, L. Aperio Bella<sup>18</sup>, G. Arabidze<sup>90</sup>, Y. Arai<sup>66</sup>, J.P. Araque<sup>126a</sup>, A.T.H. Arce<sup>45</sup>, F.A. Arduh<sup>71</sup>, J-F. Arguin<sup>95</sup>, S. Argyropoulos<sup>42</sup>, M. Arik<sup>19a</sup>, A.J. Armbruster<sup>30</sup>, O. Arnaez<sup>30</sup>, V. Arnal<sup>82</sup>, H. Arnold<sup>48</sup>, M. Arratia<sup>28</sup>, O. Arslan<sup>21</sup>, A. Artamonov<sup>97</sup>, G. Artoni<sup>23</sup>, S. Asai<sup>155</sup>, N. Asbah<sup>42</sup>, A. Ashkenazi<sup>153</sup>, B. Åsman<sup>146a,146b</sup>, L. Asquith<sup>149</sup>, K. Assamagan<sup>25</sup>, R. Astalos<sup>144a</sup>, M. Atkinson<sup>165</sup>, N.B. 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 R.J. Thompson<sup>84</sup>, A.S. Thompson<sup>53</sup>, L.A. Thomsen<sup>36</sup>, E. Thomson<sup>122</sup>, M. Thomson<sup>28</sup>, R.P. Thun<sup>89,\*</sup>,  
 M.J. Tibbetts<sup>15</sup>, R.E. Ticse Torres<sup>85</sup>, V.O. Tikhomirov<sup>96,ag</sup>, Yu.A. Tikhonov<sup>109,c</sup>, S. Timoshenko<sup>98</sup>,  
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 M. Trotter-McDonald<sup>15</sup>, M. Trovatelli<sup>134a,134b</sup>, P. True<sup>90</sup>, L. Truong<sup>164a,164c</sup>, M. Trzebinski<sup>39</sup>,  
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 S. Turchikhin<sup>99,af</sup>, D. Turecek<sup>128</sup>, R. Turra<sup>91a,91b</sup>, A.J. Turvey<sup>40</sup>, P.M. Tuts<sup>35</sup>, A. Tykhonov<sup>49</sup>,  
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 C. Unverdorben<sup>100</sup>, J. Urban<sup>144b</sup>, P. Urquijo<sup>88</sup>, P. Urrejola<sup>83</sup>, G. Usai<sup>8</sup>, A. Usanova<sup>62</sup>, L. Vacavant<sup>85</sup>,  
 V. Vacek<sup>128</sup>, B. Vachon<sup>87</sup>, C. Valderanis<sup>83</sup>, N. Valencic<sup>107</sup>, S. Valentini<sup>20a,20b</sup>, A. Valero<sup>167</sup>,  
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 G. Vardanyan<sup>177</sup>, R. Vari<sup>132a</sup>, E.W. Varnes<sup>7</sup>, T. Varol<sup>40</sup>, D. Varouchas<sup>80</sup>, A. Vartapetian<sup>8</sup>, K.E. Varvell<sup>150</sup>,

F. Vazeille<sup>34</sup>, T. Vazquez Schroeder<sup>87</sup>, J. Veatch<sup>7</sup>, F. Veloso<sup>126a,126c</sup>, T. Velz<sup>21</sup>, S. Veneziano<sup>132a</sup>, A. Ventura<sup>73a,73b</sup>, D. Ventura<sup>86</sup>, M. Venturi<sup>169</sup>, N. Venturi<sup>158</sup>, A. Venturini<sup>23</sup>, V. Vercesi<sup>121a</sup>, M. Verducci<sup>132a,132b</sup>, W. Verkerke<sup>107</sup>, J.C. Vermeulen<sup>107</sup>, A. Vest<sup>44</sup>, M.C. Vetterli<sup>142,d</sup>, O. Viazlo<sup>81</sup>, I. Vichou<sup>165</sup>, T. Vickey<sup>139</sup>, O.E. Vickey Boeriu<sup>139</sup>, G.H.A. Viehhauser<sup>120</sup>, S. Viel<sup>15</sup>, R. Vigne<sup>30</sup>, M. Villa<sup>20a,20b</sup>, M. Villaplana Perez<sup>91a,91b</sup>, E. Vilucchi<sup>47</sup>, M.G. Vincter<sup>29</sup>, V.B. Vinogradov<sup>65</sup>, I. Vivarelli<sup>149</sup>, F. Vives Vaque<sup>3</sup>, S. Vlachos<sup>10</sup>, D. Vladoiu<sup>100</sup>, M. Vlasak<sup>128</sup>, M. Vogel<sup>32a</sup>, P. Vokac<sup>128</sup>, G. 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Zoccoli<sup>20a,20b</sup>, M. zur Nedden<sup>16</sup>, G. Zurzolo<sup>104a,104b</sup>, L. Zwalinski<sup>30</sup>.

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany NY, United States of America

<sup>3</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

<sup>4</sup> (a) Department of Physics, Ankara University, Ankara; (c) Istanbul Aydin University, Istanbul; (d)

Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup> LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

<sup>7</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America

<sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

<sup>9</sup> Physics Department, University of Athens, Athens, Greece

- <sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece
- <sup>11</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>12</sup> Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
- <sup>13</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia
- <sup>14</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway
- <sup>15</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
- <sup>16</sup> Department of Physics, Humboldt University, Berlin, Germany
- <sup>17</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- <sup>18</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>19</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics, Dogus University, Istanbul; <sup>(c)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- <sup>20</sup> <sup>(a)</sup> INFN Sezione di Bologna; <sup>(b)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- <sup>21</sup> Physikalisches Institut, University of Bonn, Bonn, Germany
- <sup>22</sup> Department of Physics, Boston University, Boston MA, United States of America
- <sup>23</sup> Department of Physics, Brandeis University, Waltham MA, United States of America
- <sup>24</sup> <sup>(a)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup> Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup> Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- <sup>25</sup> Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- <sup>26</sup> <sup>(a)</sup> National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(b)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(c)</sup> University Politehnica Bucharest, Bucharest; <sup>(d)</sup> West University in Timisoara, Timisoara, Romania
- <sup>27</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>28</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>29</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>30</sup> CERN, Geneva, Switzerland
- <sup>31</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- <sup>32</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>33</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(d)</sup> School of Physics, Shandong University, Shandong; <sup>(e)</sup> Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; <sup>(f)</sup> Physics Department, Tsinghua University, Beijing 100084, China
- <sup>34</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- <sup>35</sup> Nevis Laboratory, Columbia University, Irvington NY, United States of America
- <sup>36</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- <sup>37</sup> <sup>(a)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy
- <sup>38</sup> <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>39</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

- 40 Physics Department, Southern Methodist University, Dallas TX, United States of America
- 41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- 42 DESY, Hamburg and Zeuthen, Germany
- 43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- 44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- 45 Department of Physics, Duke University, Durham NC, United States of America
- 46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- 47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
- 48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- 49 Section de Physique, Université de Genève, Geneva, Switzerland
- 50 <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- 51 <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- 52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- 53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- 54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- 55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- 56 Department of Physics, Hampton University, Hampton VA, United States of America
- 57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- 58 <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup> ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- 59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- 60 <sup>(a)</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, The University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- 61 Department of Physics, Indiana University, Bloomington IN, United States of America
- 62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 63 University of Iowa, Iowa City IA, United States of America
- 64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- 65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- 66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 67 Graduate School of Science, Kobe University, Kobe, Japan
- 68 Faculty of Science, Kyoto University, Kyoto, Japan
- 69 Kyoto University of Education, Kyoto, Japan
- 70 Department of Physics, Kyushu University, Fukuoka, Japan
- 71 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 72 Physics Department, Lancaster University, Lancaster, United Kingdom
- 73 <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 74 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 75 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- 76 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 77 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- 78 Department of Physics and Astronomy, University College London, London, United Kingdom



- <sup>79</sup> Louisiana Tech University, Ruston LA, United States of America
- <sup>80</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- <sup>81</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden
- <sup>82</sup> Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
- <sup>83</sup> Institut für Physik, Universität Mainz, Mainz, Germany
- <sup>84</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- <sup>85</sup> CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>86</sup> Department of Physics, University of Massachusetts, Amherst MA, United States of America
- <sup>87</sup> Department of Physics, McGill University, Montreal QC, Canada
- <sup>88</sup> School of Physics, University of Melbourne, Victoria, Australia
- <sup>89</sup> Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- <sup>90</sup> Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- <sup>91</sup> <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>92</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- <sup>93</sup> National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- <sup>94</sup> Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- <sup>95</sup> Group of Particle Physics, University of Montreal, Montreal QC, Canada
- <sup>96</sup> P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- <sup>97</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- <sup>98</sup> National Research Nuclear University MEPhI, Moscow, Russia
- <sup>99</sup> D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- <sup>100</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- <sup>101</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>102</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>103</sup> Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- <sup>104</sup> <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>105</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- <sup>106</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- <sup>107</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>108</sup> Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- <sup>109</sup> Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- <sup>110</sup> Department of Physics, New York University, New York NY, United States of America
- <sup>111</sup> Ohio State University, Columbus OH, United States of America
- <sup>112</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>113</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- <sup>114</sup> Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- <sup>115</sup> Palacký University, RCPTM, Olomouc, Czech Republic

- <sup>116</sup> Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- <sup>117</sup> LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- <sup>118</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>119</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>120</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>121</sup> <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>122</sup> Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- <sup>123</sup> Petersburg Nuclear Physics Institute, Gatchina, Russia
- <sup>124</sup> <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>125</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- <sup>126</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; <sup>(b)</sup> Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Department of Physics, University of Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- <sup>127</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- <sup>128</sup> Czech Technical University in Prague, Praha, Czech Republic
- <sup>129</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- <sup>130</sup> State Research Center Institute for High Energy Physics, Protvino, Russia
- <sup>131</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>132</sup> <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>133</sup> <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>134</sup> <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>135</sup> <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- <sup>136</sup> DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- <sup>137</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- <sup>138</sup> Department of Physics, University of Washington, Seattle WA, United States of America
- <sup>139</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>140</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>141</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany
- <sup>142</sup> Department of Physics, Simon Fraser University, Burnaby BC, Canada
- <sup>143</sup> SLAC National Accelerator Laboratory, Stanford CA, United States of America
- <sup>144</sup> <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- <sup>145</sup> <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand,

Johannesburg, South Africa

<sup>146</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden

<sup>147</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden

<sup>148</sup> Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

<sup>149</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

<sup>150</sup> School of Physics, University of Sydney, Sydney, Australia

<sup>151</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan

<sup>152</sup> Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

<sup>153</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

<sup>154</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

<sup>155</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

<sup>156</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

<sup>157</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

<sup>158</sup> Department of Physics, University of Toronto, Toronto ON, Canada

<sup>159</sup> <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON, Canada

<sup>160</sup> Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

<sup>161</sup> Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

<sup>162</sup> Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

<sup>163</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

<sup>164</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

<sup>165</sup> Department of Physics, University of Illinois, Urbana IL, United States of America

<sup>166</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

<sup>167</sup> Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

<sup>168</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada

<sup>169</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

<sup>170</sup> Department of Physics, University of Warwick, Coventry, United Kingdom

<sup>171</sup> Waseda University, Tokyo, Japan

<sup>172</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

<sup>173</sup> Department of Physics, University of Wisconsin, Madison WI, United States of America

<sup>174</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

<sup>175</sup> Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

<sup>176</sup> Department of Physics, Yale University, New Haven CT, United States of America

<sup>177</sup> Yerevan Physics Institute, Yerevan, Armenia

<sup>178</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

<sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom

<sup>b</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>c</sup> Also at Novosibirsk State University, Novosibirsk, Russia

<sup>d</sup> Also at TRIUMF, Vancouver BC, Canada

- <sup>e</sup> Also at Department of Physics, California State University, Fresno CA, United States of America
- <sup>f</sup> Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
- <sup>g</sup> Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal
- <sup>h</sup> Also at Tomsk State University, Tomsk, Russia
- <sup>i</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>j</sup> Also at Università di Napoli Parthenope, Napoli, Italy
- <sup>k</sup> Also at Institute of Particle Physics (IPP), Canada
- <sup>l</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>m</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- <sup>n</sup> Also at Louisiana Tech University, Ruston LA, United States of America
- <sup>o</sup> Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- <sup>p</sup> Also at Department of Physics, National Tsing Hua University, Taiwan
- <sup>q</sup> Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- <sup>r</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
- <sup>s</sup> Also at CERN, Geneva, Switzerland
- <sup>t</sup> Also at Georgian Technical University (GTU), Tbilisi, Georgia
- <sup>u</sup> Also at O Chadai Academic Production, Ochanomizu University, Tokyo, Japan
- <sup>v</sup> Also at Manhattan College, New York NY, United States of America
- <sup>w</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>x</sup> Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- <sup>y</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>z</sup> Also at School of Physics, Shandong University, Shandong, China
- <sup>aa</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- <sup>ab</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>ac</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy
- <sup>ad</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- <sup>ae</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
- <sup>af</sup> Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- <sup>ag</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia
- <sup>ah</sup> Also at Department of Physics, Stanford University, Stanford CA, United States of America
- <sup>ai</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- <sup>aj</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- <sup>ak</sup> Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
- <sup>al</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- \* Deceased